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14. ABSTRACT
The main accomplishments are:

1. Introduction analysis and implementation of correlation based passive sensor imaging
2. Beanforming algorithms for coherent interferometry
3. Fultering algorithms for imaging in heavy clutter

15. SUBJECT TERMS
Imaging in Complex Media

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Final Report for Research under Grant AFOSR FA9550-08-1-0089 on Imaging in Random Media for the Period 03/01/08-03/31/11 (with no-cost extension)

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1 Introduction and Summary

As in the title of the research grant, our main effort is in the interdisciplinary, mathematically and computationally oriented study of imaging in complex (random) media. Successful research was carried out in the following areas:

- Beamforming algorithms and enhanced stability of coherent interferometry (papers 1,2). This work is a significant theoretical advance and improvement of the coherent interferometric imaging (CINT) method that we introduced in 2005 in order to stabilize the imaging of reflectors in weakly scattering random media. In paper 1 we show analytically that for a certain class or random media with weak scattering, the random travel time models, CINT imaging has much better signal to noise ratio (SNR) than conventional migration (back-propagation) methods. This is the first time that analytically explicit results were obtained that quantify the advantages of CINT. The fact that the resolution of images in CINT is somewhat reduced was already known (obtained in our 2005 paper) but was re-derived in paper 1 in order to make clear the tradeoff between resolution loss and SNR gain with CINT. In paper 2 we show that there is a new fast algorithm for computing CINT that has some very significant advantages: It can be implemented in hardware in the time domain by a sequence of delay-and-sum steps, including a windowing step that accounts for the enhanced statistical stability of CINT. Another important feature of this algorithm is that the images are always positive functions as they have the form of an energy. This is also a stabilizing feature.

- Passive sensor imaging with ambient noise sources (papers: 18,12,6,7,8). This work was done almost entirely during the period of the grant, that is, it is a new topic. It contains the following main accomplishments: (i) A demonstration that the Green's function for wave propagation in an ergodic cavity can be recovered exactly by cross correlation of signals at two points when there is only a single illuminating noise source. (ii) The systematic use of the stationary phase method to estimate travel times from recorded noise signals under different ambient noise conditions. (iii) A new theoretical formulation for imaging reflectors with passive sensors using only ambient, opportunistic noise sources. Extensive numerical simulations amplify and validate the theory. We have also applied these methods to indoor source localization in the microwave regime using real data obtained with a source-antenna system at Stanford. One graduate student was involved in this project (T. Callaghan) one postdoctoral visitor (N. Czink), and one senior collaborator (J. Garnier).

- Imaging in strong clutter (papers 3,4). This is a new research topic that was initiated during the period of the grant. It is well known that detection and imaging in strongly inhomogeneous media (heavy clutter) is very difficult if not impossible. A general and effective algorithm has been developed that can filter out and minimize clutter effects. It is based on the windowed Fourier transform (the local cosine transform) and the singular value decomposition of the sensor data. A theoretical analysis of this algorithm has been given for randomly layered media. However, numerical simulations indicate that the method works well in general clutter. One postdoctoral visitor (R. Alonzo) and two long-time collaborators were involved in this project (L. Borcea and C. Tsogka).

- Filtering layering effects in imaging (papers 13,11). This work is the precursor to the strong clutter method of the previous item. It is also a filtering method but the filter is based on a travel time transformation that is designed to work only in layered media and, indeed, it does not generalize to media that tend to have isotropic clutter. But this filter is very effective in strongly anisotropic (layered) media. One graduate student (F. Queto) and two long-time collaborators were involved in this project (L. Borcea and C. Tsogka).

- Imaging with intensities only (paper 5). This is a new project that deals with coherent imaging (imaging in homogeneous media) when only field intensity measurements are recorded by the array sensors. Semidefinite programming (optimization) methods are used in an original way to give very good results when imaging sparse reflectors and when we are in high signal-to-noise regimes. A lot more work is needed in this emerging area, which could have many applications since intensity only sensors tend to be inexpensive and therefore can be be extensively deployed. One graduate student was involved in this project (A. Chai) and one senior collaborator (M. Moscoso).

- Autofocus and motion estimation in synthetic aperture radar (paper 9). This is also a new project in which we have developed autofocus methods based on a phase space formulation (Wigner transform) of the array data and the image. We have also used this approach for target motion estimation with SAR. But we have not been able so far to combine effectively autofocus methods with motion estimation. One graduate student was involved (T. Callaghan) and one senior collaborator (L. Borcea).

- Multiscale computing, homogenization and uncertainty quantification (papers 14,15). This is a new project in the area of inverse problems (not imaging directly) where the issue is the estimation of unknown coefficients of partial differential equations when partial information about the solution is given and the unknown coefficients could have microstructure, in addition to the overall properties we want to estimate. The multiscale computing method developed and analyzed is general and promising. The inverse problem is, however, limited to one space dimension at present. Much more work needs to be done here. One postdoctoral visitor was involved (J. Nolen).

- Imaging edges of extended objects (paper 19). This is work that was essentially finished just before the grant started. It is restricted to homogeneous media and includes substantial theoretical contributions. During the period of the grant we worked at length on extensions to randomly inhomogeneous media and a paper is currently in preparation. One postdoctoral visitor was involved (F. Guevara-Vasquez) and one senior collaborator (L. Borcea).

- Optimal directional properties of small antennas (paper 10). This work was completed early during the grant and deals only with antennas in homogeneous media. The idea is to use prolate spheroidal wave functions (the inverse filter) to focus optimally the radiation field of a small (sub-wavelength) antenna. We have worked extensively on the generalization of these ideas to random media but only recently we have obtained some encouraging results. One graduate student was involved (T. Callaghan) and two senior collaborators (L. Borcea and J. Garnier).

- Time reversal communication systems (paper 17). This paper was done some time before this grant but went through several revisions during the refereeing process. No work has been done in this area during the grant period.

2 Graduate students, postdoctoral visitors and collaborators

Two graduate students obtained their PhD during the period of the grant: T. Callghan (2010) now a postdoctoral visitor at Rice University, and A. Chai (2010) now working in the financial services industry. Visitors during the grant period were: J, Nolen, N. Czink, F. Guevara-Vasquez, M. Moscoso, L. Borcea, C. Tsogka, J. Garnier. One graduate student is expected to finish in 2011 (N. West, working on uncertainty quantification) and one more in 2012 (T. Yang, working on uncertainty quantification).

3 Awards and major lectures

May 2008, ten lectures on imaging sponsored by the Conference Board of Mathematical Sciences (CBMS) at Rice University. Five lectures on imaging at Hong Kong University of Science and Technology in December 2008. A plenary lecture at SIAM meeting December 2009. The William Benter Prize in Applied Mathematics June 2010. AMS J. Willard Gibbs Lecture January 2011.

4 Publications

All papers that are listed below and have not been published yet because they are either in the refereeing process or are accepted and on queue to appear are posted on the PI's web site: http://math.stanford.edu/∼papanico

4.1 Publications in 2011

1. Enhanced Statistical Stability in Coherent Interferometric Imaging, L. Borcea, J. Garnier, G. Papanicolaou and C. Tsogka. Submitted for publication.
2. Coherent Interferometric Imaging, Time Gating and Beamforming, L. Borcea, J. Garnier, G. Papanicolaou and C. Tsogka. Submitted for publicaton.

4.2 Publications in 2010

3. Detection and imaging in strongly backscattering randomly layered media, R. Alonzo, L. Borcea, G. Papanicolaou and C. Tsogka. Inverse Problems 27 (2011) 025004 (36pp).
4. Adaptive time-frequency detection and filtering for imaging in heavy clutter, L. Borcea, G. Papanicolaou and C. Tsogka. Submitted to SIAM Journal on Imaging Sciences (19pp).
5. Array imaging using intensity-only measurements, A. Chai, M. Moscoso and G. Papanicolaou. Inverse Problems 27 015005 (20pp).
6. Resolution analysis for imaging with noise, Josselin Garnier and George Papanicolaou. Inverse Problems, 26 (2010) 074001 (22pp).

7. Resolution enhancement from scattering in passive sensor Imaging with Cross Correlations, Josselin Garnier and George Papanicolaou. Submitted to the SIAM Journal on Imaging Sciences (33pp).

8. Correlation-based Radio Localization in an Indoor Environment, Thomas Callaghan, Nicolai Czink, Arogyaswami Paulraj and George Papanicolaou. Submitted for publication (20pp).

9. Synthetic Aperture Radar Imaging with Motion Estimation and Autofocus, Liliana Borcea, Thomas Callaghan and George Papanicolaou. Submitted for publication (50pp).

10. A universal filter for enhanced imaging with small arrays, Liliana Borcea, Thomas Callaghan, Josselin Garnier and George Papanicolaou. Inverse Problems, vol 26 (2010) 015006, 29pp.

11. Filtering random layering effects in imaging, Liliana Borcea, F. Gonzalez del Cueto, George Papanicolaou and Chrysoula Tsogka. SIAM Journal on Multiscale Model. Simul. Vol 8 (2010) pp. 751-781.

4.3 Publications in 2009

12. Passive Sensor Imaging Using Cross Correlations of Noisy Signals in a Scattering Medium, Josselin Garnier and George Papanicolaou. SIAM J. Imaging Sci. Volume 2, Issue 2, pp. 396-437 (2009).

13. Filtering deterministic layer effects in imaging, Liliana Borcea, F. Gonzalez del Cueto, George Papanicolaou and Chrysoula Tsogka. SIAM Journal of Multiscale Modeling and Simulation, vol 7 (2009), pp. 1267-1301.

14. Fine scale uncertainty in parameter estimation for elliptic equations. J. Nolen and G. Papanicolaou. Inverse Problems, 25, (2009), 115021 (22pp).

4.4 Publications in 2008

15. A Framework for Adaptive Multiscale Methods for Elliptic Problems. J. Nolen, G. Papanicolaou and O. Pironneau. SIAM Journal on Multiscale Modeling and Simulation, 7, (2008), pp. 171-196.

16. Analysis of Pulse Propagation Through an One-Dimensional Random Medium Using Complex Martingales, J. Garnier and G. Papanicolaou. Stochastics and Dynamics, Vol 8(1), (2008), pp. 127-138.

17. Spatial focusing and intersymbol interference in multiple input single output time reversal communication systems A. Kim, P. Kyritsi, P. Blomgren and G. Papanicolaou. IEEE J. Ocean Engineering, 33, (2008), 341-355.

18. Identification of Green's Functions Singularities by Cross Correlation of Noisy Signals, Claude Bardos, Josselin Garnier and George Papanicolaou. Inverse Problems, vol 24 (2008), 015011 (26pp).

19. Edge illumination and imaging of extended reflectors, Liliana Borcea, George Papanicolaou and Fernando Guevara Vasquez. SIAM Journal on Imaging Sciences, vol 1 (2008), pp. 75-114.

REPORT OF INVENTIONS AND SUBCONTRACTS

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